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Dynamic Smoothness Control for Dual-Motor-Independent-Drive Electric Vehicles Based on Kalman Filter

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Abstract

In order to reduce the lateral dynamics shock caused by mechanical gap of a dual-motor-independently-drive electric vehicle while the accelerator pedal was quickly pressed down, the Kalman filter was adopted to design a dynamics smoothness controller. Simulation results proved the effectiveness of the control strategy - it could improve the smoothness of the lateral dynamics effectively. The effect on the control performance of the value of process noise - Q was discussed. It is important to select an appropriate Q to balance the improvement of dynamics smoothness and the increased response time for the accelerator pedal.

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keywords: dynamics smoothness control; independent drive; electric vehicle; Kalman filter;

1. Introduction

Independent motor drive electric vehicles have much more potential in dynamics control than the vehicles with single motor drive. Such as Direct Yaw Control(DYC) and Anti-Slip Regulation(ASR)[1] can be realized for the motor's rapidly response. The typical response time of motor is only several milliseconds, for this complicated control strategies can be realized[2]. Many studies have been done on the independent drive electric vehicles [3].

A dual-motor-independent-drive electric vehicle named "BIT-MIDI" was completed[4], as shown in Fig.1. A problem appeared during vehicle tests that there exits lateral dynamics shock and the steering

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wheel spin accidently when the accelerator pedal was quickly pressed down. Moreover, the shock is not the same each time.

Fig.1. The dual-motor-independent-drive electric vehicle “BIT-MIDI”.

Nomenclature

T_1^{org}	Torque produced by motor No.1
T_2^{org}	Torque produced by motor No.2
T_1^{out}	Torque act on drive wheel No.1
T_2^{out}	Torque act on drive wheel No.2
δ_{t1}	Time delay of torque act on drive wheel No.1
δ_{t2}	Time delay of torque act on drive wheel No.2
M	Moment produced by mechanical gap
a	Distance between the drive wheel and CG

As shown in Fig.2, the torque generated by the two motors will possibly not act on the two drive wheels simultaneously due to the difference of mechanical gap of the two independent transmission components.

$$\delta_{t1} \neq \delta_{t2} \tag{1}$$

The mechanical gap is unpredictable and will cause random lateral dynamics response of the vehicle.

$$M = \left(T_1^{out} - T_2^{out}\right) \cdot a \tag{2}$$

The lateral dynamics shock caused by M makes the driver and passengers uncomfortable and it may cause unpredictable danger conditions. In order to reduce the influence of the mechanical gap, the Kalman filter is adopted in this paper. It is hard to find the same research on this problem yet. The research result is helpful to improve the drive performance of independent drive electric vehicles.

Fig.2 (a)The structure of drive system;(b)The cause of lateral dynamics shock;

2. modeling

2.1 Vehicle modelling

The simplified vehicle model has seven degrees of freedom including the longitudinal and lateral displacement, the yaw of rotation of the vehicle, and the rotation of the four wheels.
The equations of dynamics of the vehicle and the four wheels are:

$$m\left(\dot{V}_x - V_y\omega_r\right) = \left(F_{x1}+F_{x2}\right)\cos\delta_f + \left(F_{x3}+F_{x4}\right) - \left(F_{y1}+F_{y2}\right)\sin\delta_f - \frac{1}{21.15}C_D A V_x^2 \tag{3}$$

$$m\left(\dot{V}_y + V_x\omega_r\right) = \left(F_{x1}+F_{x2}\right)\sin\delta_f + \left(F_{y1}+F_{y2}\right)\cos\delta_f \tag{4}$$

$$I_z\,\dot{\omega}_r = a\left(\left(F_{x1}+F_{x2}\right)\sin\delta_f + \left(F_{y1}+F_{y2}\right)\cos\delta_f\right) - b\left(F_{y3}+F_{y4}\right)$$
$$+\frac{B_f}{2}\left((F_{x2}-F_{x1})\cos\delta_f + (F_{y1}-F_{y2})\sin\delta_f\right) + \frac{B_r}{2}(-F_{x3}+F_{x4}) \tag{5}$$

$$I_{w1}\,\dot{\omega}_1 = T_{d1} - F_{x1}r_r - F_{z1}fr_r \tag{6}$$

$$I_{w2}\,\dot{\omega}_2 = T_{d2} - F_{x2}r_r - F_{z2}fr_r \tag{7}$$

$$I_{w3}\,\dot{\omega}_3 = -F_{x3}r_r - F_{z3}fr_r \tag{8}$$

$$I_{w4}\,\dot{\omega}_4 = -F_{x4}r_r - F_{z4}fr_r \tag{9}$$

Where, m means the vehicle mass; V_x and V_y mean the longitudinal and lateral velocity; ω_r and ω_i mean the yaw rate of the vehicle and the i th wheel; F_{xi} and F_{yi} mean the tire force of the i th wheel in the longitudinal and lateral direction; δ_f means the front wheel steering angle; C_d and A mean the coefficient of drag and the front area of the vehicle; I_z and I_{zi} means yaw inertia moment of the vehicle and the i th wheel; a , b mean the distance between the vehicle's center of gravity to the front and rear axles; B_f and B_r mean the front and rear wheel base; T_{di} means the drive torque on the i th wheel;

F_{zi} means the vertical force of the i th wheel; f and r_r mean the coefficient of rolling resistance and the rotation radius of the wheels.

2.2 Driver-in -loop modeling

In order to achieve more reliable simulation results, a real accelerator pedal is included in the simulation loop using the dSPACE/MicroAutoBox. The vehicle model is combined with the driver-in-loop model. So the vehicle model can get a real input to improve the preciseness of simulation.

Fig.3 shows the simulation system. It includes the PC to control the progress of the simulation via ControlDesk. The dSPACE/MicroAutobox with the accelerator pedal controlled by a human driver is also included. The driver-in-loop simulation model can acquire the driver's input and output the demand dynamics parameters.

Fig.3. The Driver-in-Loop simulation system.

3. Control Strategy

3.1 The lateral dynamics response caused by the random mechanical gap

In the dual-motor-independent-drive electric vehicle, the torque generated by the motor is transmitted through the reduction gear box and propeller shaft to the left and right drive wheel independently. In a single-motor-drive electric vehicle, the mechanical gap will cause torque shock in the longitudinal direction, but no yaw moment is produced. But in a dual-motor-independent-drive electric vehicle, yaw moment is produced.

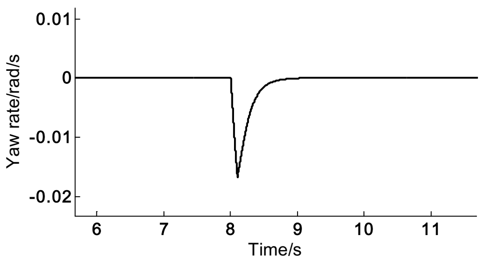

Fig.4 The yaw moment caused by mechanical gap.

Moreover, the mechanical gap will be a random value between zero and the maximum value. So the yaw moment caused by the mechanical gap is unpredictable while the accelerator pedal is quickly pressed down. Fig.4 shows the yaw moment caused by the mechanical gap with a step input of the accelerator pedal.

3.2 Dynamics smoothness control based on Kalman filter

Due to the randomness of the mechanical gap, it is impossible to compensate the torque difference of the two independent drive wheels precisely. Kalman filter is widely used in stochastic optimal control system. The dynamics smoothness control can be realized based on Kalman filter.

Take the output of the driver model's accelerator pedal as a discrete linear random system. The equations of the system are:

$$X_k = \Phi_{k,k-1} X_{k-1} + \Gamma_{k,k-1} W_{k-1} \tag{10}$$

$$Z_k = H_k X_k + V_k \tag{11}$$

Where, X_k means the state vector of the system; Z_k means the observation noise vector; W_k means the process noise vector; $\Phi_{k,k-1}$ means the state tranmission matrix; $\Gamma_{k,k-1}$ means the noise input matrix; H_k means the observation matrix.

The statistical characteristics of the system's process noise and observation noise are:

$$E\left[W_k W_j^T\right] = Q_k \delta_{kj} \tag{12}$$

$$E\left[V_k V_j^T\right] = R_k \delta_{kj} \tag{13}$$

Where, Q_k means the variance matrix of process noise; R_k means the variance matrix of observation noise; δ_{kj} means the Kronecker- δ function.

The basic equations of Kalman filter are as follows[5].

$$\hat{X}_{k,k-1} = \Phi_{k,k-1} \hat{X}_{k-1} \tag{14}$$

$$\hat{X}_k = \hat{X}_{k,k-1} + K_k \left[Z_k - H_k \hat{X}_{k,k-1} \right] \tag{15}$$

$$K_k = P_k H_k^T R_k^{-1} \tag{16}$$

$$P_{k,k-1} = \Phi_{k,k-1} P_{k-1} \Phi_{k,k-1}^T + \Gamma_{k,k-1} Q_{k-1} \Gamma_{k,k-1}^T \tag{17}$$

$$P_k = \left[I - K_k H_k \right] P_{k,k-1} \tag{18}$$

In Fig.5(a), the Kalman filter controller block is placed between the driver and the vehicle dynamics model, which will prepare the output of the driver's accelerator pedal for the vehicle model to reduce the uncertain yaw moment caused by the random mechanical gap, further improve the vehicle's lateral dynamics smoothness. Fig.5(b) shows a step signal input and its output curve applied the model of Kalman filter controller. The different values of process variance/Q and measurement variance/R will lead to different output curve shapes.

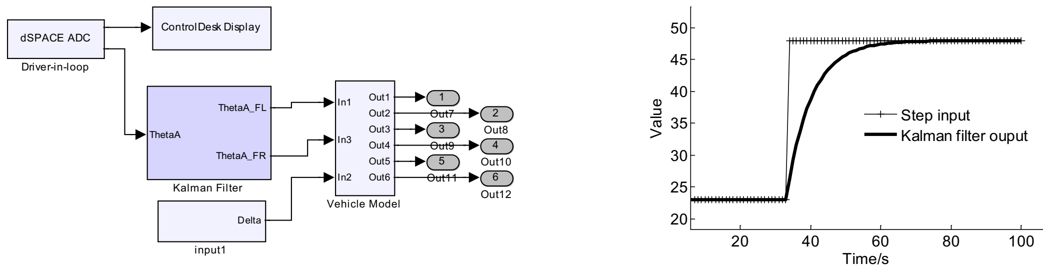

Fig.5. (a)The vehicle model combined with the Kalman filter controller; (b) The Kalman filter controller output acting on a step signal input.

4. Simulation results and discussion

Keep the vehicle's speed at around 50 km/h, then the driver outputs a 0-0.65 step of accelerator pedal signal, the sampled accelerator pedal output is shown in Fig.6(a).

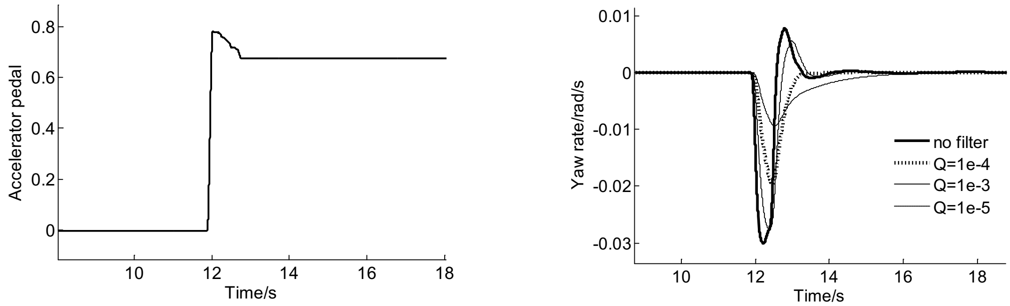

Fig.6. (a)Accelerator pedal output;(b) The vehicle's yaw rate.

The process noise (Q) highly influences the filter performance. By changing the value of Q, different filter performances can be achieved. Fig.6(b) shows the vehicle's yaw rate caused by the mechanical gap, the four different simulation results are achieved under different conditions, they are - without control and with Kalman filter control of three different process noise of $Q=10^{-4}$, $Q=10^{-3}$ and $Q=10^{-5}$, respectively. The peak value of the yaw rate without control is the highest, which cause a sharp lateral dynamics shock. The results produced by Kalman filter control are better than the non-control results.

With the reduction of Q, the peak value of yaw rate caused by mechanical gap reduces significantly, and the same with the sideslip angle, as shown in Fig.7(a). Thus the smoothness control is verified to be valid.

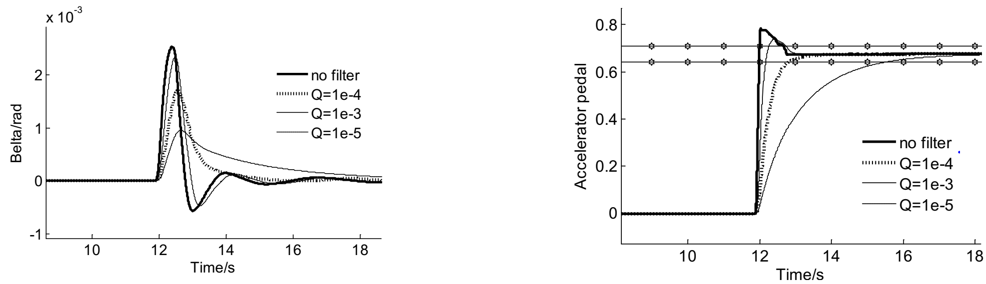

Fig.7. (a)The vehicle's sideslip angle.**(b)**The accelerator pedal output.

However, the response time of the accelerator pedal increases with the reduction of Q, as shown in Fig.7(b). It will take longer time for the vehicle to response to the accelerator pedal. So it is important to balance the reduction of peak value of lateral dynamics shock and the response time increased.

Table 1 Simulation result of different value of Q.

Q	10^{-3}	10^{-4}	10^{-5}
Yaw rate reduced/	8.65%	34.81%	68.67%
Sideslip angle reduced/	7.10%	32.27%	62.51%
Response time increased/s	0.185	0.788	3.400

Table 1 shows the improvement of the lateral dynamics shock of the three different value of Q and the response time increased. It can be concluded from the results that a value of 10^{-4} of Q is most appropriate for the Kalman filter controller. It improves the lateral dynamics smoothness by about 35% and doesn't lead to unacceptable response time of the accelerator pedal.

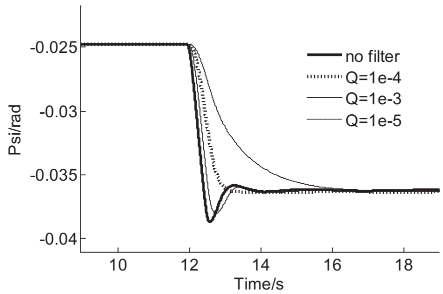

Fig.8. The vehicle's yaw angle.

Fig.8 shows the yaw angle caused by the mechanical gap. It can be concluded that although the yaw angle with Kalman control changes slowly, the final value is the same, no matter what the value of Q is. Thus it indicates that the Kalman filter controller cannot help to reduce the deviation distance caused by the mechanical gap. The controller can only reduce the peak value of lateral dynamics shock. A feedback controller may take effect to reduce the deviation distancein the future research.

5. Conclusion

A smoothness control method based on Kalman filter is proposed to help reducing the peak value of the lateral dynamics shock caused by the mechanical gap for a dual-motor-independent-drive electric vehicle. A vehicle model is built for simulating the effects of the mechanical gap and the improved results by the Kalman filter controller. The simulation results show that the Kalman filter controller can reduce the peak value of the yaw rate and side-slip angle caused by the mechanical gap remarkably. By changing the value of process noise/Q, different control performance can be achieved. The developed Kalman filter controller can improve the smoothness of lateral dynamics, but the response time of the accelerator pedal is longer. Thus an appropriate selection of Q is important. Finally, this control method cannot reduce the deviation distance caused by the mechanical gap, and this is left for future study.

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